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Creep Rupture Behavior of Stirling Engine Materials

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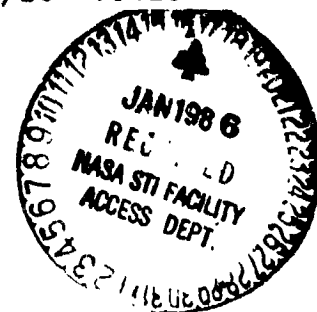
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this paper, have been subjected to a simulated braze cycle heat treatment. This paper will summarize the creep-rupture technology of the prototype and the present candidate cast heater head alloys in various heat treated conditions as well as casting techniques. As with all summarizations we will compare the candidate alternate iron-base alloys to the prototype alloy, HS-31 and recommend that a new design criteria for the cast heater head components be considered and adopted.

MATERIALS AND EXPERIMENTAL PROCEDURES

The nominal composition of the cast alloys evaluated in creep-rupture tests is given in table I. The two alloys NASAUT 4G-A1 and NASACC-1 were developed under contract to NASA Lewis by United Technologies (ref. 4) and AiResearch Manufacturing Co (ref. 5).

Prior to creep-rupture testing the alloys were given a simulated braze-cycle heat treatment based upon "best effort" estimates of joining practices likely to be encountered. Table II shows the heat treatment each of the alloys had received prior to testing and represents a chronological change in the braze joining philosophy. HS-31 and XF-818 had a simulated braze cycle based upon anticipated temperatures and times without regard to the properties of the heater head tubes. The alloys NASAUT 4G-A1 and NASACC-1 which were developed later in the technology program were tested in conditions which reflect the manufacturer recommended heat treatment for the cast alloy. Also a brazing cycle and aging cycle were introduced, which reflects the present recommended solutioning and aging treatment required for the heater head tube material, CG-27. All heat treatments were conducted in vacuum, at pressures generally in the 1.5 mPa regime.

RESULTS AND DISCUSSION

Figure 1 shows the resultant creep-rupture data for the prototype HS-31 alloys and its first alternate candidate alloy XF-818 tested at 760 °C in both air and 15 MPa hydrogen (refs. 6 and 7). Statistically, there appears to be no effect of test environment on the creep-rupture lives of HS-31 or XF-818. The note worthy point is that XF-818 with approximately two-thirds of the long-time (3500 hr) rupture strength of HS-31 has been successfully tested in an engine with no creep-rupture failures (ref. 8). Figure 2 shows the 3500 hr design criteria curves for the HS-31 and XF-818 alloys. The present MOD-1 criteria for rupture life is a stress level of 119 MPa at 775 °C.

The recently developed alloys NASAUT 4G-A1 and NASACC-1 were creep-rupture tested in air at NASA Lewis. Figure 3 shows the results of air creep-rupture tests at 775 °C. The NASAUT 4G-A1 well illustrates the superiority of the directionally solidified (DS) casting technique over that of the conventional equiaxed castings. The DS material has a projected stress level capability of about 175 MPa at 3500 hr while the equiaxed material (HT-1) has a stress level of about 135 MPa. The DS material, presently represents typical stress-rupture properties attainable with the present composition. A change in the cylinder/regenerator housing casting techniques may be warranted to utilize the approximate 25 percent strength improvement over the base heat treatment. The HT-2 curve which is the simulated braze cycle plus aging does indicate an approximate additional 20 percent loss in the projected 3500 hr stress-rupture strength.

CREEP RUPTURE BEHAVIOR OF STIRLING ENGINE MATERIALS

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SUMMARY

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The automotive Stirling engine, being investigated jointly by the Department of Energy and NASA Lewis as an alternate to the internal combustion engine, uses high-pressure hydrogen as the working fluid. The long-term effects of hydrogen on the high temperature strength properties of materials is relatively unknown. This is especially true for the newly developed low-cost iron base alloy NASAUT 4G-A1. This iron-base alloy when tested in air has creep-rupture strengths in the directionally solidified condition comparable to the cobalt base alloy HS-31. The equiaxed (investment cast) NASAUT 4G-A1 has superior creep-rupture to the equiaxed iron-base alloy XF-818 both in air and 15 MPa hydrogen.

INTRODUCTION

A joint program of the Department of Energy and NASA Lewis is under way to develop the Stirling engine as an alternate to the internal combustion engine for automotive applications. The Stirling engine is an external combustion engine that offers the advantage of potential high fuel economy, multiple fuel capability, low emissions, low noise, and low vibrations compared to present internal combustion automotive engines. The most critical engine component from a materials viewpoint is the heater head consisting of the heater tubes, cylinders and regenerator housings. A goal of the Automotive Stirling Engine Program is to achieve a 30 percent increase in fuel economy over internal combustion engines of similar size and vintage (refs. 1 and 2). To achieve these operating characteristics, the Stirling engine will operate near 820 °C and use hydrogen, at a pressure of 15 MPa, as the working fluid.

The long-term effects of high pressure hydrogen at high temperature on the physical and mechanical properties of high temperature iron-base alloys are generally unknown. Candidate alloys for Stirling engine applications must not only meet all the property requirements in air as well as in high-pressure hydrogen, but must also be of low cost to be compatible with automotive applications (ref. 3). The prototype engine used a cast cobalt base alloy, HS-31, for the cylinders and regenerator housings. Because of limited availability of cobalt and its high cost, cobalt free iron-base alloys will be required for the heater head materials.

A continuing supporting materials research and technology program at NASA Lewis has identified the cast alloys XF-818, NASAUT 4G-A1 (ref. 4) and NASACC-1 (ref. 5) as candidate replacements for the cobalt containing prototype alloy HS-31. Generally, these iron-base superalloys were studied, in air and high pressure (15 MPa) hydrogen, in the recommended heat treated condition. However common manufacturing practice indicated the heater head materials may be subjected to a brazing process to join heater head tubes to the cast cylinder heads. The candidate cylinder/regenerator heater head materials described in

If it is assumed that an equivalent 20 percent loss would occur in the DS material following a braze cycle plus aging, its 3500 hr stress-rupture strength would be approximately 140 MPa or about 17 percent above the present design criteria. The NASACC-1 alloy has an indicated 3500 hr stress-rupture strength of 80 MPa. Presently it is believed that a 20 percent deficit in stress-rupture strength is too great of a loss and this alloy will be dropped from the automotive engine testing program.

High pressure (15 MPa) hydrogen creep-rupture tests were conducted on the NASAUT 4G-Al alloy (ref. 9) in the HT-2 heat treated condition. Figure 4 compares the rupture life of NASAUT 4G-Al tested in 15 MPa hydrogen and in air. While the curves show that testing in hydrogen yield higher 3500 hr stress-rupture strengths, 145 MPa compared to 115 MPa in air, this improvement is not believed to be significant due to the large amount of scatter in the hydrogen data (ref. 9). The important point to be noted is that the NASAUT 4G-Al did not suffer a drastic or catastrophic loss of properties in hydrogen as was feared because of its high (1.5 percent) carbon level.

The 3500 hr rupture stress levels for the prototype HS-31 cobalt alloy and the presently utilized XF-818 alloys when compared to the NASAUT 4G-Al alloy, as shown in figure 5, indicate that the NASAUT 4G-Al would be a feasible alternate alloy. The DS material in its recommended heat treated condition (no braze cycle) appears slightly stronger than the HS-31 in the braze cycle condition. Whereas the equiaxed NASAUT 4G-Al in the braze cycled plus aged condition (considered a worst case condition) is comparable to the XF-818 alloy which itself has never exhibited a creep-rupture failure.

Creep-rupture as the design criteria for the cast cylinder/regenerator housings appears to be a very restrictive parameter especially when it is realized that a rupture failure has never occurred in a cylinder or regenerator housing. It is believed that a design criteria based upon some finite strain level, perhaps in the 0.5 to 1.0 percent range, would allow for a better assessment of engine efficiency and performance and be relatable to other important failure modes. Figure 6 which shows the projected 3500 hr air stress levels to limit creep strain to 1 percent indicates that what is considered the worst case condition for the NASAUT 4G-Al alloy (HT-2, braze cycled plus aged with an equiaxed grain structure) has approximately a 30 percent stress advantage over XF-818.

CONCLUSIONS AND RECOMMENDATION

- (1) The NASAUT 4G-Al, in the directionally solidified condition has superior 1 percent creep strength which should be utilized in the design of the Automotive Stirling Engine.
- (2) The NASAUT 4G-Al alloy in the investment cast (equiaxed), simulated braze cycled plus aged condition has a comparable rupture strength to the present cast cylinder/regenerator alloy XF-818 at 775 °C.
- (3) The NASAUT 4G-Al alloy in the investment cast (equiaxed), simulated braze cycled plus aged condition has superior 1 percent creep strength to the present cast cylinder/regenerator alloy XF-818 at 775 °C.

(4) Based on the materials research programs in support of the automotive Stirling engine it is concluded that manufacture of the engine is feasible from the low-cost iron-base NASAUT 4G-Al alloy

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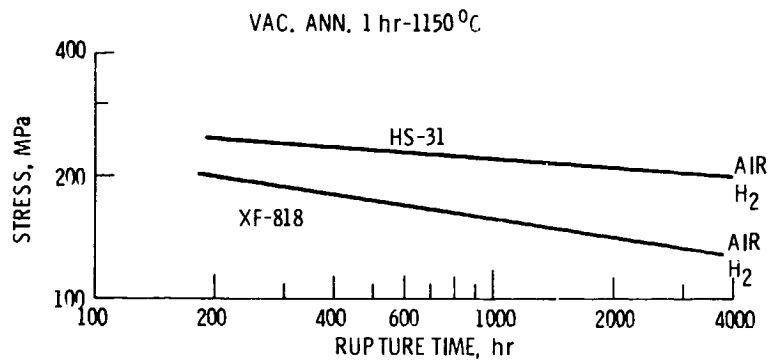


Figure 1. - Air and 15 MPa hydrogen 760 °C rupture lives for HS-31 and XF-818.

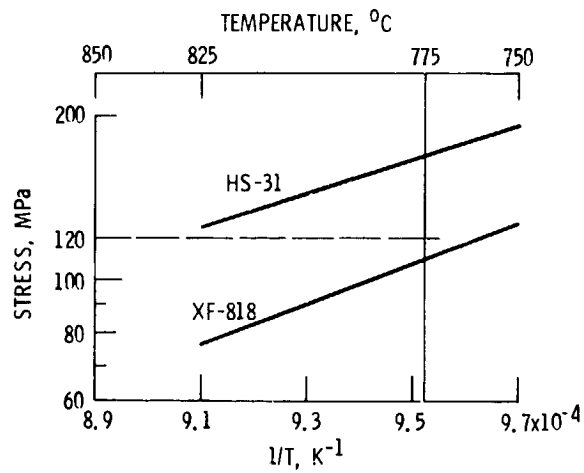


Figure 2. - 3500 hr Air and 15 MPa H₂ rupture stress versus temperature design criteria curves for HS-31 and XF-818.

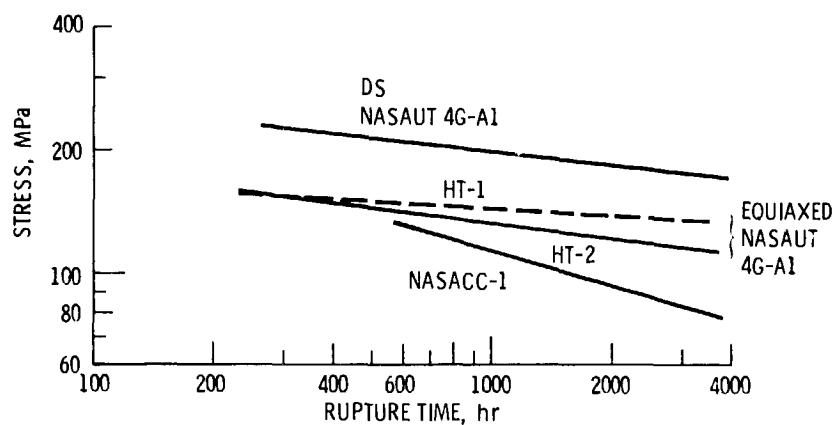


Figure 3. - 775 °C Rupture lives for NASAUT 4G-A1 and NASACC-1 tested in air.

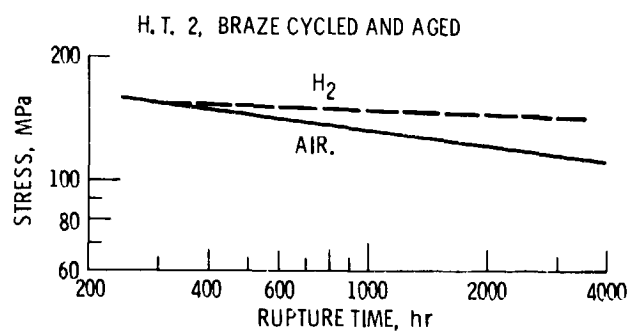


Figure 4. - 775 °C Rupture life curves of NASAUT 4G-A1 in air and 15 MPa hydrogen for the condition.

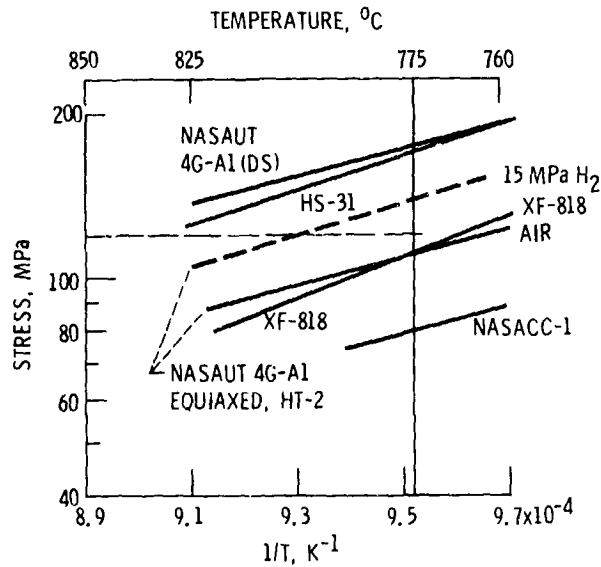


Figure 5. - 3500 hr Rupture stress versus temperature design criteria curves for candidate Stirling engine alloys compared to MOD-1 design criteria (3500 hr life at 775 °C/119 MPa).

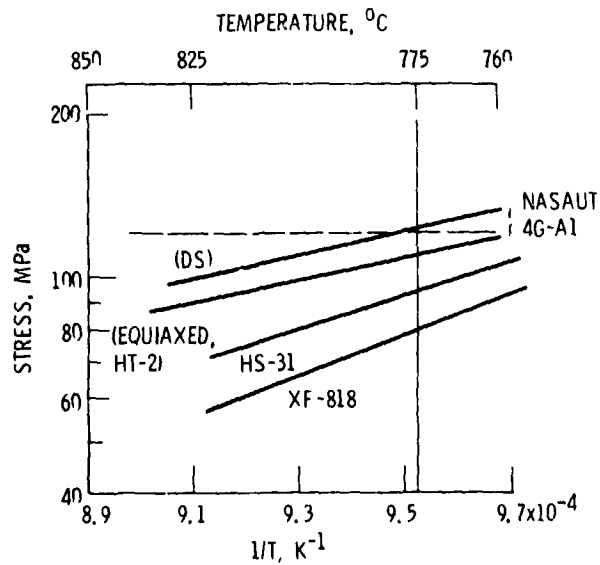


Figure 6. - 3500 hr stress for one percent strain versus temperature for candidate Stirling engines alloys tested in air.

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